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UNCERTAINTIES IN LCA

A system boundary identification method for life cycle assessment

Tao Li · Hongchao Zhang · Zhichao Liu · Qingdi Ke · Leo Alting

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Abstract
Purpose Life cycle assessment (LCA) is a useful tool for quantifying the overall environmental impacts of a product, process, or service. The scientific scope and boundary definition are important to ensure the accuracy of LCA results. Defining the boundary in LCA is difficult and there are no commonly accepted scientific methods yet. The objective of this research is to present a comprehensive discussion of system boundaries in LCA and to develop an appropriate boundary delimitation method.
Methods A product system is partitioned into the primary system and interrelated subsystems. The hierarchical relationship of flow and process is clarified by introducing flow- and process-related interventions. A system boundary curve model of the LCA is developed and the threshold rules for judging whether the system boundary satisfies the research requirement are proposed. Quantitative criteria from environmental, technical, geographical and temporal dimensions are presented to limit the boundaries of LCA. An algorithm is developed to identify an appropriate boundary by searching the process tree and evaluating the environmental impact contribution of each process while it is added into the studied system.
Results and discussion The difference between a limited system and a theoretically complete system is presented. A case study is conducted on a color TV set to demonstrate and validate the method of boundary identification. The results showed that the overall environmental impact indicator exhibits a slow growth after a certain number of processes considered, and the gradient of the fitting curve trends to zero gradually. According to the threshold rules, a relatively accurate system boundary could be obtained.
Conclusions It is found from this research that the system boundary curve describes the growth of life cycle impact assessment (LCIA) results as processes are added. The two threshold rules and identification methods presented can be used to identify system boundary of LCA. The case study demonstrated that the methodology presented in this paper is an effective tool for the boundary identification.

Keywords Life cycle assessment · Process tree · Search algorithm · System boundary · Threshold rule

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1 Introduction

Life cycle assessment (LCA) is a method for analyzing and assessing the potential environmental impact and resource utilization of a product throughout its entire lifecycle, i.e., from raw materials acquisition, through production and utilization phases, to waste management (EPA 2006). There are four phases in an LCA study: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. In the phases of Scope Definition and Inventory

Analysis, the inputs should ideally be traced back to raw materials as found in nature, and the outputs should ideally be emissions to nature (Finnveden et al. 2009). That is to say "Inputs to the system that have been drawn from the environment without previous human transformation and outputs released to the environment without subsequent human transformations" (ISO 14040 2006a).

Due to the unbounded life cycle process flow, the related life cycle processes are numerous even for a simple product, the specific data required is so enormous and is therefore impossible to fully collect (Raynolds et al. 2000). It is difficult to set the boundaries for an LCA with such high completeness (Finnveden et al. 2009). Thus, in the application of life cycle studies, a critical step is to set up the boundaries for process flow presentation and data collection. However, the current LCA practices and the ISO standards on LCA impose practical difficulties for drawing a boundary around an LCA problem (EPA 2006; ISO 14040 2006a). According to ISO 14040 and ISO 14044 (2006a, b) standards, a system boundary is determined by an iterative process in which an initial system boundary is chosen, and then further refinements are made by including new unit processes that are shown to be significant by sensitivity analysis. However, these decisions on inclusion or exclusion of processes (the cut-off criteria) are typically not made on a scientific basis (Suh et al. 2004; Lindfors et al. 1995). In particular, the determinations of which processes can be excluded from the system boundary are difficult because many excluded processes have never been assessed by the practitioners, and therefore their negligibility cannot be guaranteed. Considering a product life cycle study, different people may select different system boundaries based on their own personal experiences, which might result in some important processes being overlooked. The boundary selection issue has become a challenging task for "comparative assertion intended to be disclosed to the public" (ISO 14044 2006b).

The principles or methods of system boundary analysis for LCA have been studied in recent years. Allocation problems along with the system boundary have received much attention, especially with respect to the difference between consequential LCA and attributional LCA. In consequential LCA, the system boundaries are defined to include the activities contributing to the environmental consequences, regardless of whether they are within or outside of the cradle-to-grave system of the product investigated. Allocation problems may then often be avoided through expanding the system boundaries to include affected processes outside the cradle-to-grave system. In contrast, for attributional LCA, allocation (partitioning) is often considered to be the correct method (Ekvall and Weidema 2004). Some researchers compared and optimized boundary analysis methods for LCA in certain areas such as waste management (Gentil et al. 2010; Merrild et al. 2008), energy generation (Williams 2004), sustainability (Ny et al. 2006), etc. In these studies, they listed all the possible assumptions for specific life cycle studies and selected the most appropriate boundaries for study purposes. Nevertheless, these methods might have their own drawbacks such as being limited to individual cases and temporal or geographical limitations. In current LCA studies, the boundary selection issue is still a critical weakness. Therefore, a scientific method of boundary identification needs to be put forward to decide which processes should be included or excluded.

In this paper, the authors explore and present a method of system boundary identification for LCA. The definitions of unit process, systems, and process tree are presented systematically. Quantitative criteria from environmental, technical, geographical, and temporal dimensions are generated to limit boundaries of LCA. A search algorithm to obtain a scientifically sound boundary is established by searching the process tree of a product system in its life cycle. A case study is conducted on a color TV set to demonstrate and validate the method of boundary identification.

2 System boundary model of the LCA

2.1 Description of product system boundaries

Clift et al. (1998) divided the product system of an LCA study into two kinds of systems, the foreground systems and the background systems. For foreground systems, primary, site-specific data will normally be collected, and for background systems, secondary data from databases, public references, or estimated data based on IO-LCA models are used. The analysis of a product life cycle will become easier if the sequence of operations associated with a product or material is broken down into a primary system and a series of subsystems. The primary system includes primary activities that directly contribute to the product's major life cycle stages such as manufacture, utilization, and recycling of the product or material. The secondary tier includes auxiliary materials or processes that interact directly with the primary activity sequence. Several tiers of auxiliary materials or processes may extend further and further from the main sequence. These individual auxiliary materials or processes are defined as subsystems that are parts of the defined production system. Figure 1 shows a general system boundary of a product. The primary system corresponds to the foreground system generally, which uses data collected and calculated by the investigator, while the subsystem corresponds to either the foreground system or the background system, which depends on the study purpose.

There are three major types of system boundaries in the LCA (Guinée 2002a, b): (1) the boundary between the product system and the environmental system, (2) the boundary between processes that are significant and insignificant to the product system (cut-off), and (3) the boundary between the

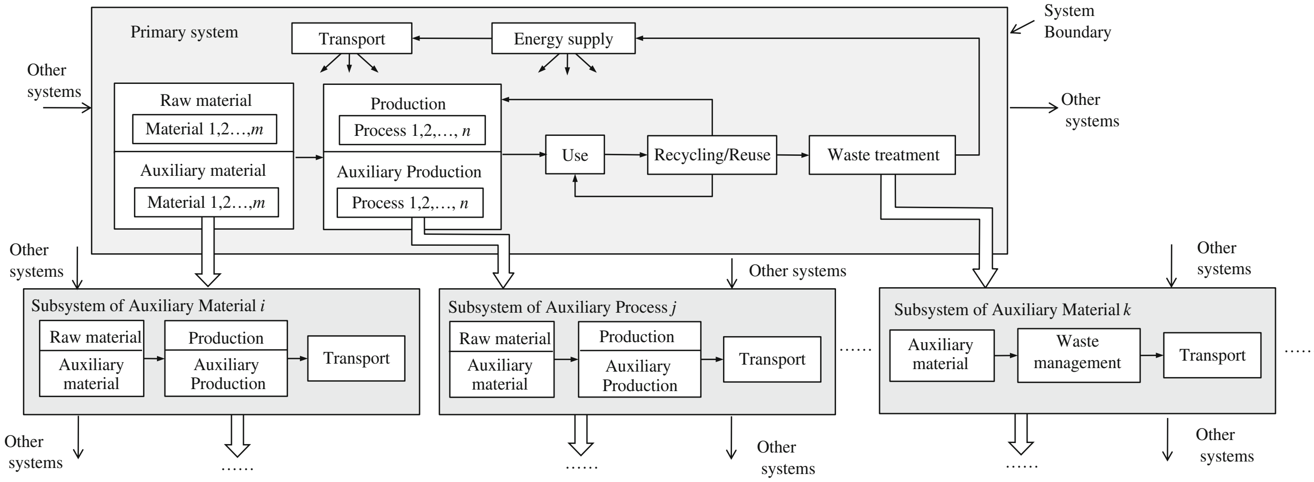


Fig. 1 The partition of interrelated systems

product system under consideration and other product systems (allocation). In this paper, the first and second of the major types will be discussed by the identification of environmental and technical systems. The third one will be solved according to the methodology of matrix-based LCA (Heijungs and Suh 2001; Hochschorner and Finnveden 2003). Temporal and geographical limits are also mentioned as system boundaries (Finnveden et al. 2009). However, these can be seen as special cases of boundaries towards the environmental systems or towards other technological systems (see Section 3.3).

In setting system boundaries, the analyst should very well understand the possible consequences of different system boundaries and the difference between a limited system and a theoretically complete system. Understanding the possible consequences of different decisions is important for evaluating tradeoffs between the accuracy of LCA results and the cost, time, or other factors invested in the study. The inputs and outputs of a unit process of a product system include product, material, energy, and waste flows (abbreviated to "the flows" in the paper). We suggest that a distinction of system boundaries can be made between flow- and process-related interventions. Flow-related interventions are the input or output flows entering or leaving the process. Process-specific interventions are the processes included in the total product system. Flow-related subsystems are trace back of flow-related interventions, while process-related subsystems are trace back of process-related interventions. For the primary system and each of its subsystem, the definition of system boundaries refers to the determination of which flow-related and process-specific subsystems should be included in the systems.

2.2 Definition and formulation of process tree

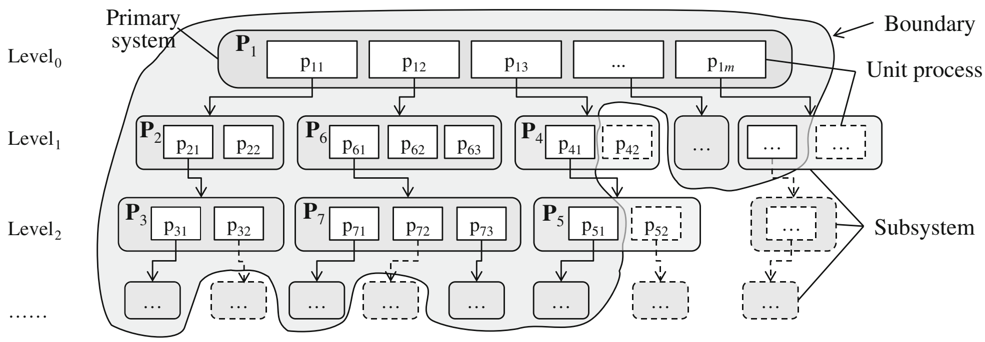
A product system is a collection of unit processes connected by flows of intermediate products which perform one or more defined functions. Unit processes (often abbreviated to processes) are the smallest portions of a product system for which data is collected during execution of an LCA. They are linked to one another by flows of intermediate product and/or waste for treatment, to other product systems by product flows, and to the environment by elementary flows, i.e., inputs from and outputs to the environment, also referred to as environmental interventions.

Life cycle process flow of a product system can be described with the tree structure diagram (Tillman et al. 1994). The primary system can be seen as the root (parent) in the process tree, which consists of the subsystems or branch processes (children). Each branch process also can be viewed as the root of its branch processes. The primary system is represented as Level 0, the branch processes of the primary system are represented as Level 1, and so on (as shown in Fig. 2). In the process tree, the primary system (root) can contain several branch processes, while each branch process has only one root. With the process tree, a life cycle inventory can be established by employing a search strategy to identify and list all the input resources and output releases in every branch process. To simplify the analysis, the partition of processes in the parent system is in such a way that each process only has one subsystem (as shown in Fig. 2). The primary system and subsystem are composed of the unit processes.

In this research, the methodology of matrix-based LCA (Heijungs and Suh 2001) is employed to define the unit process.

Definition 1 The unit process is defined as a vector $\mathbf{p}=(p_1, p_2, \ldots, p_m)^T$, where, p_i $(1\leq i\leq m)$ is the flow of the unit process, and the dimension of $\mathbf{p}$ is n. $\mathbf{p}$ can be partitioned into two distinct parts: $\mathbf{p}=(\mathbf{a}|\mathbf{b})^T=(a_1, a_2, \ldots, a_m \,|\, b_1, b_2, \ldots, b_m)^T$, where vector $\mathbf{a}$ represents the flows within the economic

Fig. 2 Process tree of a product life cycle



systems, called the technology vector; vector **b** represents the environmental interventions of the unit process, called the intervention vector; and $m_1+m_2=m$.

For instance, the vector basis of the color TV set is:

$$\mathbf{p}_i = \begin{pmatrix} \text{Color TV set} \\ \text{MJ of electricity} \\ \text{Disposed color TV set} \\ \text{Hour of color TV work} \\ \text{kg of glass} \\ \text{kg of steel} \\ \vdots \\ \text{kg of CO}_2 \\ \text{kg of CO} \\ \vdots \end{pmatrix}$$

Based on the vector basis above, the vector of a color TV set production can be described as $\mathbf{p}_2=(1, -229.23, 0, 0, 0, 0, \ldots, 0, 0, \ldots)^{\mathrm{T}}$. The subsystem of $\mathbf{p}_2$ includes the processes of materials production. For example, the vector of the production of glass, $\mathbf{p}_5=(0, -9.12, 0, 0, 1, 0, \ldots, 1.09, 2.68\text{E-}04, \ldots)^{\mathrm{T}}$, the vector of the production of steel, $\mathbf{p}_6=(0, -10.81, 0, 0, 0, 1, \ldots, 9.49, 0.11, \ldots)^{\mathrm{T}}$, etc. Here, the negative co-ordinates indicators are inputs, while the positive co-ordinates indicators are outputs.

The unit processes have been standardized and modularized as individual standard processes. The development of a better LCA database is the precondition for storing and reading the unit processes. The flows of the unit processes are available in the LCA database, while primary site-specific data can be used to complement insufficient data by LCA researchers. Since the final demand also called reference flow may not match with the flows of the unit process, a set of factors (transformation function) are needed to scale up or down the flows of the unit processes in order to satisfy the final demand.

Definition 2 The set of the unit processes is defined as the system **P**, called the life cycle matrix, $\mathbf{P}=[\mathbf{p}_i]$, where $i=1, 2, \ldots, n$. If the studied object is a primary system, then we mark it as $\mathbf{P}_{\text{pri}}$, and if the studied object is a flow-related subsystem, then we mark it as $\mathbf{P}_{\text{sub-f}}$, if the studied object is a process-related subsystem, then we mark it as $\mathbf{P}_{\text{sub-p}}$.

Based on the definition of a tree, an entire product system throughout its life cycle (PLC) can be defined recursively as a process tree.

Definition 3 The product system of an LCA is defined as a process tree PLC=(S, R), where S is the set of primary system and subsystems of the studied system. R is the set of the relationships among S. If $S=\varnothing$, then the studied system is empty; else PLC satisfies the following conditions:

(1) There is a distinguished node in S called $\mathbf{P}_{\text{pri}}$, which has no parent in R.
(2) If $R=\varnothing$, then the studied product system only considers $\mathbf{P}_{\text{pri}}$; else R is a set of ordered pair on S, and $S-\{\mathbf{P}_{pri}\}$ can be divided into m subsystems($\mathbf{P}_{\text{sub-f}}$ or $\mathbf{P}_{\text{sub-p}}$) called $\text{PLC}_1, \text{PLC}_2, \ldots, \text{PLC}_m$, each of whose roots are connected by $r_i \in R$ $(1 \le i \le m)$ to $\mathbf{P}_{\text{pri}}$, for any couple of $u \ne v\,(1 \le u \le m,\ 1 \le v \le m)$, $\text{PLC}_u \cap \text{PLC}_v = \varnothing$. Each subsystem is said to be a *child* of $\mathbf{P}_{\text{pri}}$ and $\mathbf{P}_{\text{pri}}$ is the *parent* of each subsystem.
(3) If $R \ne \varnothing$, then I) if the subsystem $\mathbf{P}_j$ is $\mathbf{P}_{\text{sub-f}}$, then $\exists r_i \in R$, $r_i=\{<p_i, \mathbf{P}_j>|\ p_i \in \mathbf{p}_{\boldsymbol{k}}, \mathbf{p}_{\boldsymbol{k}} \in \mathbf{P}_k, \mathbf{P}_k=\text{parent}(\mathbf{P}_j)\}$, else II) if the subsystem $\mathbf{P}_j$ is $\mathbf{P}_{\text{sub-p}}$, then $\exists r_j \in R, r_j=\{<\mathbf{p}_{\boldsymbol{k}}, \mathbf{P}_j>|\ \mathbf{p}_{\boldsymbol{k}} \in \mathbf{P}_k, \mathbf{P}_k=\text{parent}(\mathbf{P}_j)\}$.

According to the definition of the process tree, a product system is broken down into a primary system and a series of subsystems. And there are two kinds of subsystems: $\mathbf{P}_{\text{sub-f}}$ and $\mathbf{P}_{\text{sub-p}}$. The set of ordered pair R describes the relationship of subsystems with their parents.

Definition 4 If the studied product system is marked as S, which is composed of the primary system and its subsystems, then the unit processes of S can be the arranged into the life cycle matrix **P**, $\mathbf{P}=[\mathbf{p}_1, \mathbf{p}_2, \ldots, \mathbf{p}_i, \ldots, \mathbf{p}_n]$, where $\mathbf{p}_i \in S$. The matrix **P** is then said to be of dimension $m \times n$.

The matrix **P** consists of all processes considered in the primary system and subsystems. Thus, the matrix **P** is exactly what is required in an LCA study of a product. **P** can be partitioned into two distinct parts (Heijungs and Suh 2001):

$\mathbf{P} = \binom{\mathbf{A}}{\mathbf{B}}$, where matrix **A** represents the flows within the economic systems, called the technology matrix. Matrix **B** represents the environmental intervenes of the studied system, called the intervention matrix. If the reference flow is represented as a vector **f**, then the inventory table of the studied system is defined as the vector of environmental interventions **g**, $\mathbf{g} = \mathbf{B}\mathbf{A}^{-1}\mathbf{f} = \mathbf{B}\mathbf{s} = \mathbf{\Lambda}\mathbf{f}$, where $\mathbf{s} = \mathbf{A}^{-1}\mathbf{f}$ is called a scaling vector, and $\mathbf{\Lambda} = \mathbf{B}\mathbf{A}^{-1}$ is called an intensity matrix.

2.3 Theoretical basis of boundary identification

LCIA establishes a linkage between the product or process and its potential environmental impacts on human health, natural environment, natural resources, and so on. Because the life cycle process flow of a product system is represented as a process tree, the scope of an LCA study becomes larger when more processes in the process tree are included in the studied system. As a result, more inventory data is required and the final environmental impact indicators will potentially become larger.

The system boundary curve model of the LCA can be presented using Fig. 3, which shows the relationship between the scope of the LCA study and the final environmental impacts. For an LCA, the environmental impact increases with the increasing mass of the input flows into the product system. At the beginning, this increase is rapid. However, with further extension of the subsystem level and addition of more auxiliary materials and processes to the system, the increase slows down. This is because the reduced increase of mass of the input flows adding to the studied system and potentially diminishing environmental impact value of the processes. Consider a point on the curve whose y value is δ and whose gradient is k_δ. When the impact exceeds this point, the increase of the value of y is negligible and $k_\delta \rightarrow 0$. Therefore, no more processes and materials need to be included in the studied system. So $\Delta\delta$ and k_δ can be considered as two thresholds to judge if the system boundary satisfies the requirement. Therefore, a more scientific method of defining the system boundary in a product LCA can be carried out by including the primary and important data and performing LCI and LCIA in iterative loops until the required precision of $\Delta\delta$ or k_δ has been achieved. The difference between a limited system and a theoretically complete system can be quantitatively understood from the boundary curve.

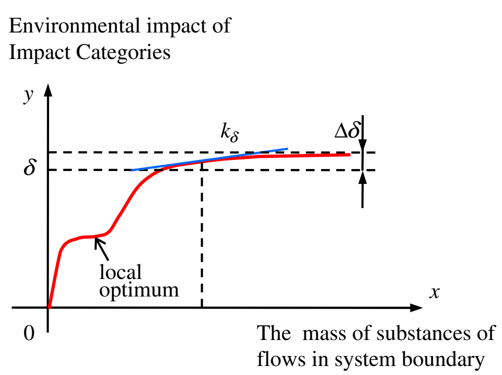


Fig. 3 The system boundary curve and the threshold of required precision

3 Quantitative criteria of boundaries identification

3.1 Constraint criteria of economic processes dimension

System boundary identification means setting criteria to specify which unit processes are part of a product system (ISO 14044 2006b). The selected system boundaries must be dependent on the purpose of the life cycle study. Without affecting the reliability of the final results, the limitation of life cycle stages may be permissible when a narrower study scope and goal are considered. There are four main options to define which processes lie within the system boundaries: cradle to gate, gate to gate, cradle to grave, and gate to grave (Jacquemin et al. 2012). So the constraint criterion of economic processes dimension is:

$$\text{Scope criterion} = \{\text{cradle to gate, gate to gate, cradle to grave, gate to grave}\}$$

As illustrated in Fig. 1, the economic processes dimension of the primary system is from cradle to grave or can be narrowed according to the goal of the study. For the subsystem, if the subsystem is about the subassemblies of the product, the economic process dimension of cradle to gate is sufficient, since all the subassemblies are installed in the product and the inventory of the subassemblies, such as utilization, maintenance and waste treatment, are included in the primary system. If the subsystem is about the auxiliary materials or processes, the economic processes dimension should be defined according to their life cycle.

3.2 Constraint criteria of geographical, temporal and technical dimensions

In addition to constraint criterion of economic processes dimensions mentioned above, system boundaries must be specified in other dimensions, such as geographical, temporal and technical coverage. The geographical and temporal dimensions of the study goal can be treated as separate steps (Heijungs et al. 1992).

ISO 14044 states that geographical coverage refers to geographical area from which data for unit processes should be collected to satisfy the goal of the study. The geographical representativeness could be global, continental, regional,

national, local or at company level. So the constraint criterion of geographical dimension is:

$$\text{Geographical criterion} = \{\text{global, continental, regional, national, local, company}\}$$

ISO 14044 states that temporal coverage refers to the desired age of data and the minimum length of time over which data should be collected. It is important to specify a base period or base year for the study, on which other choices can be based. Temporal dimension has become more and more important in recent years, so that other analysis, such as mode of analysis, can be based (Guinée 2002a, b). With regard to temporal representativeness, Heijungs stated that it should be determined similar to geographical representativeness. Generally, a rough indication will suffice, for example, 1998, 2010, or within the last 5 years (Heijungs et al. 1992). Therefore, the constraint criterion of temporal dimension is:

$$\text{Temporal criterion} = t, \text{or Temporal criterion} = [t_1, t_2].$$

The technical dimension taken as the point of departure for data collection in the inventory analysis should match the geographical and temporal coverage of the study.

ISO 14044 states that technology coverage refers to specific technology or technology mix (e.g. weighted average of the actual process mix, best available technology or worst-operating unit). For different goal and scope of the study, the data of state-of-the-art technology, prototype technology or best available technology should be selected.

3.3 Constraint criteria of environmental interventions and impact categories

ISO 14044 states that "inputs and outputs selected for an LCA depend on the goal and scope of the study." and "The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration." Todd and Curran (1999) mentioned two main options for narrowing the coverage of environmental interventions and impacts:

(1) Focusing on specific environmental impacts (for example, CO_2) and
(2) Establishing criteria to be used as "showstoppers," the inventory proceeds according to the established guidelines, which can result in an immediate decision whether the data are needed or not.

So the constraint criterion of impact categories dimension is:

$$\text{Impact categories criterion} = \{\text{Global Warming Potential, Ozone Depletion Potential, Resource Depletion Potential, Photochemical Ozone Creation Potential, Acidification Potential, Human Health Potential, Terrestrial Toxicity Potential, Aquatic Toxicity Potential, Eutrophication Potential}, \ldots\}.$$

In inventory collection, while the input and output are tracked back to elementary flows, the data outside of impact categories criterion will not be collected.

3.4 Cut-off criteria for environmental and technical system

The more difficult task is how to include more representative flows and processes in the scope of the study. Cut-off criteria can be used to separate the analyzed product system from the nature and the rest of the technical system by defining the inputs and outputs included in or excluded from the system. For example, ISO 14049 (2000) and Guinée (Guinée 2002a, b) explained that "if a flow contributes less than X% (mass/mass) to the total mass inflow of a specific process, the flow may be removed from further analysis."

However, cut-off criteria have their own problems. First of all, it is impossible to determine what is 100 %, since not all flows are known in terms of mass. Secondly, it is relatively easy to decide which flows are excluded from a system according to the product's overall weight (Guinée 2002a, b), but it is more difficult to estimate contribution of a process or subsystem to the overall environmental impact of the system. Making the identification of inputs or outputs based on mass contribution alone may result in important inputs or outputs being omitted from the study, so energy and environmental relevance should also be used as cut-off criteria (Guinée 2002a, b). Cut-off criteria should be avoided as much as possible by using input–output modeling or by estimating flows from similar flows (Crawford 2008; Guinée 2002a, b).

As mentioned above, system boundaries definition can be simplified by considering flow- and process-related interventions. It is proposed that the priority level of process-related interventions is higher than that of flow-related interventions. The priority level criterion is "process-related intervention has higher priority over flow-related intervention."

The aforementioned analysis indicates that the first decision is which processes or subsystems are included in the studied system when the identification of the system boundary is carried out. The second decision is which flows should be included in the considered process or subsystem. For example, in Fig. 4, firstly, the process-related subsystem $\mathbf{P}_j$ of process $\mathbf{p}_{i1}$ is considered in the studied system, and then the flow-related

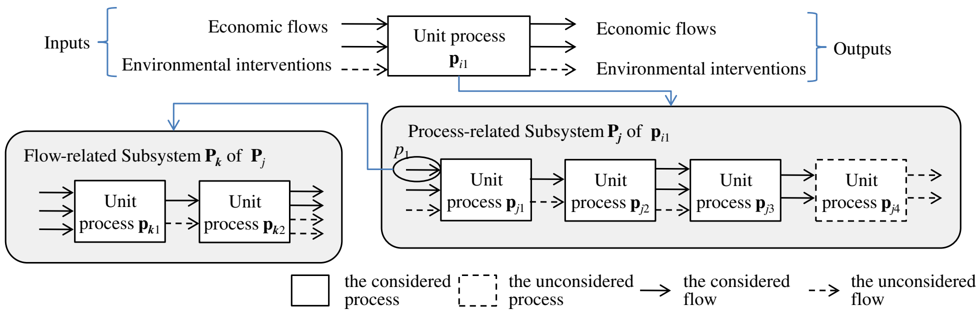


Fig. 4 The priority level of process-related interventions and flow-related interventions

subsystem $\mathbf{P}_k$ of one flow p_1 of $\mathbf{P}_j$ is considered in the studied system.

In this research, the collected data will not be omitted from the computations no matter how small they are. The cut-off criteria will not be used unless the data cannot be obtained under the current conditions. In the case of insufficient data, the possible significant issues of the cut-off will be assessed quantitatively and qualitatively based on LCI and LCIA. In order to avoid getting stuck in the local optimum in Fig. 3, the final system boundary of the analyzed system should, as far as possible, include primary relevant life cycle stages and processes that are operated within the product system. Therefore, a search algorithm is put forward to ensure that all primary processes are actually included in the modelled system by evaluating the quantitative environmental impact indicators of the unit processes.

4 Identification method of system boundaries

4.1 Quantitative environmental impact evaluation

Since the product system is modularized as a process tree, the next step is to evaluate the environmental impact of the unit process $\mathbf{p}_i$ and the system S_i based on the vector of environmental interventions $\mathbf{g}$, which can be calculated by Definition 4. Global Warming Potential (GWP) of $\mathbf{p}_i$ is:

$$GWP(\mathbf{p}_i) = \sum_{j=1}^{m} EFGWP_j \times g_j \tag{1}$$

where GWP($\mathbf{p}_i$) is the impact indicator of emission of various greenhouse gases; EFGWP$_i$ is the GWP characterization factor of the substance g_i, which is expressed in kg CO_2-equivalent. Inventory data $g_i \in \mathbf{g}$ is the mass of the substance g_i released in kg and $\mathbf{g}$ is the vector of environmental interventions derived from $\mathbf{p}_i$.

The environmental impacts of all the known unit processes are evaluated and saved in the database, which forms the basis of developing the method to identify the boundary of an LCA.

If the studied product system is marked as S_i, $\mathbf{p}_1, \mathbf{p}_2, \ldots,$ $\mathbf{p}_i \in S_i$, the matrix $\mathbf{P}=[\mathbf{p}_1, \mathbf{p}_2, \ldots, \mathbf{p}_i]$, $\mathbf{P} = \left(\frac{\mathbf{A}}{\mathbf{B}}\right)$, the vector $\mathbf{g}$ of system S_i is $\mathbf{g}=\mathbf{BA}^{-1}\mathbf{f}$, the dimension of $\mathbf{g}$ is m. Then GWP of S_i is:

$$GWP(S_i) = \sum_{j=1}^{m} EFGWP_j \times g_j \tag{2}$$

If one more process $\mathbf{p}_{i+1}$ is added into the studied system, then $S_{i+1}=S_i \cup \{\mathbf{p}_{i+1}\}$, $\mathbf{P}'=[\mathbf{p}_1, \mathbf{p}_2, \ldots, \mathbf{p}_i, \mathbf{p}_{i+1}]$, $\mathbf{P}' = \left(\frac{\mathbf{A}'}{\mathbf{B}'}\right)$.

So the vector $\mathbf{g}'$ of the system S_{i+1} is $\mathbf{g}'=\mathbf{B}'\mathbf{A}'^{-1}\mathbf{f}$, the dimension of $\mathbf{g}'$ is m'. The GWP of S_{i+1} is:

$$GWP(S_{i+1}) = \sum_{j=1}^{m'} EFGWP'_j \times g'_j \tag{3}$$

In Fig. 3, the y axis indicates the value of the environmental impact indicator GWP(S_i). The x axis indicates the sum of the mass of the input flows of S_i. The system boundary curve for GWP can be plotted with more processes added into the studied system. Impact evaluation methods of the other Impact Categories are similar to that of GWP.

The system boundary curve also can be plotted by the overall environmental impact indicator after completing the steps of grouping and weighting. The equation is:

$$EI(S_i) = \sum_{k=1}^{l} V_k \cdot K(S_i) \quad or \quad EI\,(S_i) = \sum_{k=1}^{l} V_k \cdot KN(S_i) \tag{4}$$

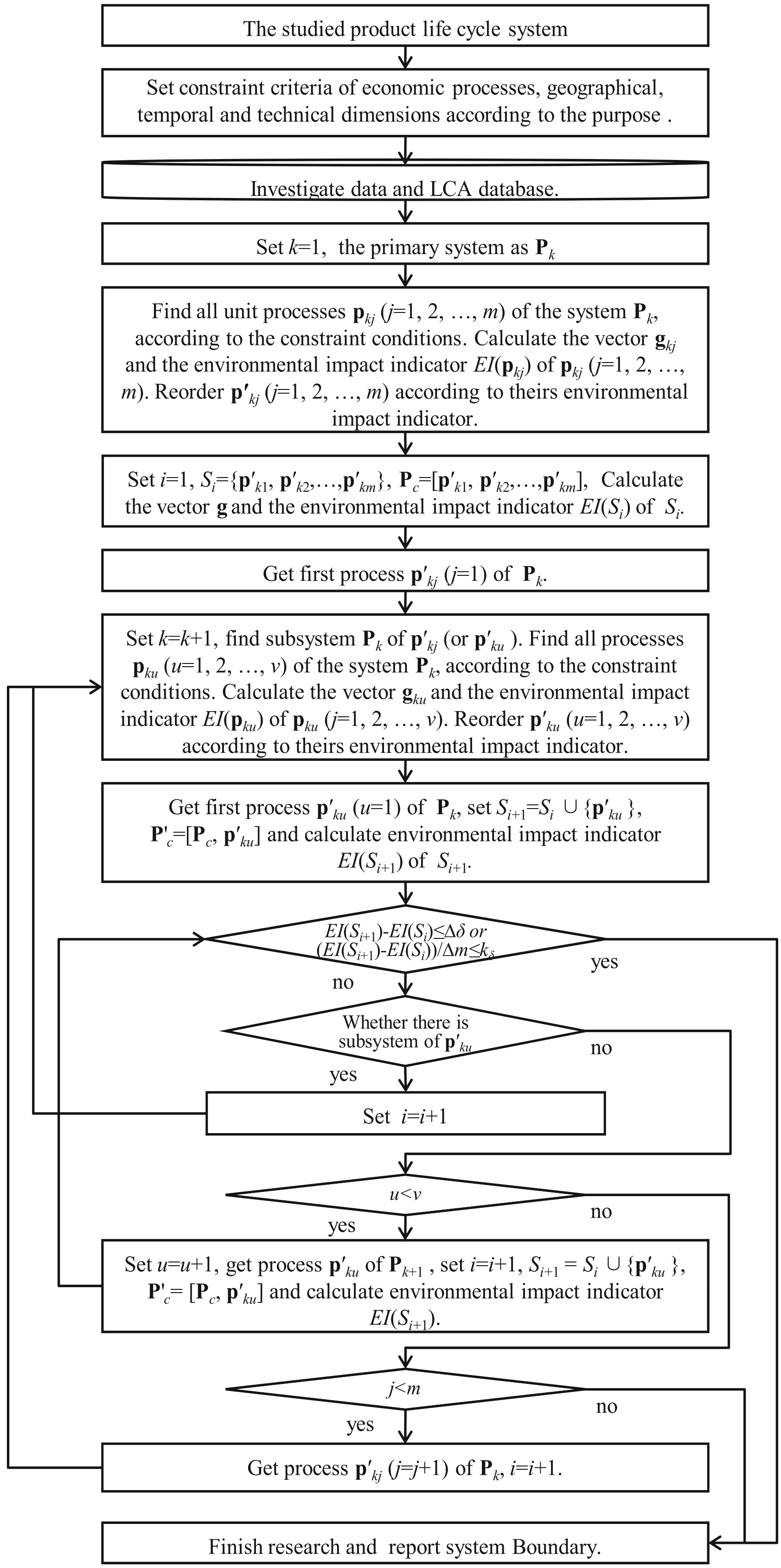
where EI(S_i) is the overall environmental impact indicator of system S_i, V_k is the weighting factor for impact category k, $K(S_i)$ is the category indicator from the characterization phase, KN(S_i) is the normalized indicator from the characterization phase, and l is the number of impact categories considered.

If one more process is added to the studied system, the overall environmental impact indicator is:

$$EI(S_{i+1}) = \sum_{k=1}^{l} V_k \cdot K(S_{i+1}) \, or \, EI(S_{i+1}) = \sum_{k=1}^{l} V_k \cdot KN(S_{i+1}) \tag{5}$$

In this situation, the y axis in Fig. 3 indicates the value of the environmental impact indicator EI(S_i). The

Fig. 5 Boundary identification procedures



Step 1:
Define the reference flow as the vector **f**, RESULT= ∅, system level is L. Initialize set SYSTEM={$\mathbf{P}_k$, L, white, RoP}, k=1, 2, …, n. Initialize sets PROCESS$_k$={$\mathbf{p}_{kj}$, $\mathbf{P}_k$, L, white} (j=1, 2, …, m) for system $\mathbf{P}_k$.

Step 2:
Set L=0. Define the current visit system is the primary system $\mathbf{S}_{pri}$, so k=1. system$_1$= {$\mathbf{P}_{pri}$, 0, gray, pri}.

Step 3:
Suppose there is only three processes($\mathbf{p}_{11}$, $\mathbf{p}_{12}$, $\mathbf{p}_{13}$) in $\mathbf{P}_{pri}$, the order of these processes resorted is $\mathbf{p}_{11}$, $\mathbf{p}_{13}$ and $\mathbf{p}_{12}$, so initialize set PROCESS$_1$={$\mathbf{p}_{1j}$, $\mathbf{P}_{pri}$, 0, gray} (j=1, 2, 3), where, process$_{11}$={$\mathbf{p}_{11}$, $\mathbf{P}_{pri}$, 0, gray}, process$_{12}$={$\mathbf{p}_{13}$, $\mathbf{P}_{pri}$, 0, gray}, process$_{13}$={$\mathbf{p}_{12}$, $\mathbf{P}_{pri}$, 0, gray.

Step 4 :
Set $\mathbf{P}_c$= [$\mathbf{p}_{11}$, $\mathbf{p}_{12}$, $\mathbf{p}_{13}$], then calculate the inventory vector $\mathbf{g}=\mathbf{BA}^{-1}\mathbf{f}$. Assess the environmental impact of $\mathbf{P}_c$ and marked it as $EI(S_1)$. Put process$_{11}$, process$_{12}$, process$_{13}$ in RESULT. Set j=1 Get process$_{11}$={$\mathbf{p}_{11}$, $\mathbf{P}_{pri}$, 0, black}.

Step 5 (1):
Find subsystem $\mathbf{P}_2$ of $\mathbf{p}_{11}$ by checking set R, set L=L+1, k=k+1, system$_2$={$\mathbf{P}_2$, 1, black, RoP}.

Step 6 (1):
There is two processes ($\mathbf{p}_{21}$, $\mathbf{p}_{22}$) in $\mathbf{P}_2$. Suppose the order of these processes resorted is $\mathbf{p}_{21}$, $\mathbf{p}_{22}$, so initialize set PROCESS$_2$={$\mathbf{p}_{2u}$, $\mathbf{P}_2$, 1, gray} (u=1, 2), where, process$_{21}$={$\mathbf{p}_{21}$, $\mathbf{P}_2$, 1, gray}, process$_{22}$={$\mathbf{p}_{22}$, $\mathbf{P}_2$, 1, gray}, Set u=1.

Step 7 (1):
Get process$_{21}$={$\mathbf{p}_{21}$, $\mathbf{P}_2$,1, black}, set $\mathbf{P}_c'$= [$\mathbf{P}_c$, $\mathbf{p}_{21}$], then calculate the inventory vector $\mathbf{g}'=\mathbf{B}'\mathbf{A}'^{-1}\mathbf{f}$. Assess the environmental impact of $\mathbf{P}_c'$ and marked it as $EI(S_2)$. Put process$_{21}$ in RESULT.
check whether $EI(S_2)-EI(S_1)\leq\Delta\delta$ *or* $(EI(S_2)-EI(S_1))/\Delta m\leq k_\delta$ is satisfied. Suppose the non-equality is not satisfied, go to **Step 8**.

Step 8 (1):
Since there is subsystem of $\mathbf{p}_{21}$, set $\mathbf{P}_c$=$\mathbf{P}_c'$ and i=i+1 go to **Step 5.**

Step 5 (2):
Find subsystem $\mathbf{P}_3$ of $\mathbf{p}_{21}$ by checking set R, set L=L+1, k=k+1, system$_3$={$\mathbf{P}_3$, 2, black, RoP}.

Step 6 (2):
There is two processes ($\mathbf{p}_{31}$, $\mathbf{p}_{32}$) in $\mathbf{P}_3$. Suppose the order of these processes resorted is $\mathbf{p}_{32}$, $\mathbf{p}_{31}$, so initialize set PROCESS$_3$={$\mathbf{p}_{3u'}$, $\mathbf{P}_3$, 2, gray} (u'=1, 2), where, process$_{31}$={$\mathbf{p}_{32}$, $\mathbf{P}_3$, 2, gray}, process$_{32}$={$\mathbf{p}_{31}$, $\mathbf{P}_3$, 2, gray}, Set u'=1.

Step 7 (2):
Get process$_{31}$={$\mathbf{p}_{32}$, $\mathbf{P}_3$, 2, black}, set $\mathbf{P}_c'$=[$\mathbf{P}_c$, $\mathbf{p}_{32}$], then calculate the inventory vector $\mathbf{g}'=\mathbf{B}'\mathbf{A}'^{-1}\mathbf{f}$. Assess the environmental impact of $\mathbf{P}_c'$ and marked it as $EI(S_3)$. Put process$_{31}$ in RESULT.
Check whether $EI(S_3)-EI(S_2)\leq\Delta\delta$ *or* $(EI(S_3)-EI(S_2))/\Delta m\leq k_\delta$ is satisfied. Suppose the non-equality is not satisfied, go to **Step 8**.

Step 8 (2):
Since there is no subsystem of $\mathbf{p}_{32}$, so check if u'<2, since it is true , so u'=u'+1, set $\mathbf{P}_c$=$\mathbf{P}_c'$ and i=i+1, go to **Step 7.**

Step 7 (3):
Get process$_{32}$={$\mathbf{p}_{31}$, $\mathbf{P}_3$, 2, black}, set $\mathbf{P}_c'$= [$\mathbf{P}_c$, $\mathbf{p}_{31}$], then calculate the inventory vector $\mathbf{g}'=\mathbf{B}'\mathbf{A}'^{-1}\mathbf{f}$. Assess the environmental impact of $\mathbf{P}_c'$ and marked it as $EI(S_4)$. Put process$_{32}$ in RESULT.
Check whether $EI(S_4)-EI(S_3)\leq\Delta\delta$ *or* $(EI(S_4)-EI(S_3))/\Delta m\leq k_\delta$ is satisfied. Suppose the non-equality is not satisfied, go to **Step 8**.

Step 8 (3):
Since there is no subsystem of $\mathbf{p}_{31}$, and check if u'<2, since it false, so check u<2, since it is true, so u=u+1, L=L−1, set $\mathbf{P}_c$=$\mathbf{P}_c'$ and i=i+1, go to **Step 7**.

Step 7 (4):
Get process$_{22}$={$\mathbf{p}_{22}$, $\mathbf{P}_2$, 1, black}, set $\mathbf{P}_c'$=[$\mathbf{P}_c$, $\mathbf{p}_{22}$], then calculate the inventory vector $\mathbf{g}'=\mathbf{B}'\mathbf{A}'^{-1}\mathbf{f}$. Assess the environmental impact of $\mathbf{P}_c'$ and marked it as $EI(S_5)$. Put process$_{22}$ in RESULT.
Check whether $EI(S_5)-EI(S_4)\leq\Delta\delta$ *or* $(EI(S_5)-EI(S_4))/\Delta m\leq k_\delta$ is satisfied. If satisfied, then quit the search and return RESULT, else set $\mathbf{P}_c$=$\mathbf{P}_c'$ and i=i+1.
Suppose the non-equality is not satisfied, go to **Step 8**.

Step 8 (4):
Since there is no subsystem of $\mathbf{p}_{22}$, and check if u<2, since it is false, so go to **Step 9**.

Step 9 (1):
Check whether j<m, since it is false, so set L=L−1, get process$_{12}$= {$\mathbf{p}_{13}$, $\mathbf{P}_{pri}$, 0, black}, go to **Step 5.**

Step 5 (3):
Find subsystem $\mathbf{P}_4$ of $\mathbf{p}_{13}$ by checking set R, set L=L+1, k=k+1, system$_4$={$\mathbf{P}_4$, 1, black, RoP}.

……

Fig. 6 Detailed steps of boundary identification procedures

x axis indicates the sum of the mass of the input flows of S_i. The system boundary curve for the overall environmental impact can be plotted with more processes added into the studied system.

With more processes and subsystems included in the studied system, the increase of GWP(S_i) or EI(S_i) slows down. So the increased values of environmental impact indicators $\Delta\delta$ and the gradient of the fitting curve k_δ can be defined as the thresholds for stopping boundary identification.

For a single environmental impact category, for example GWP, the two threshold rules are:

$$GWP\ (S_{i+1}) - GWP\ (S_i) \leq \Delta\delta \quad or\ [GWP(S_{i+1}) - GWP(S_i)]\Big/\Delta m \leq k_\delta \tag{6}$$

For overall environmental impact, the two threshold rules are:

$$EI\ (S_{i+1}) - EI\ (S_i) \leq \Delta\delta \quad or [EI(S_{i+1}) - EI(S_i)]\Big/\Delta m \leq k_\delta \tag{7}$$

4.2 Search algorithm

Once the quantitative constraint criteria and environmental impact evaluation formulas are set up for the process tree of a product system throughout its life cycle (PLC), we can undertake the task of boundary identification for the studied system using a mathematic method. In order to reach the value of δ quickly and avoid getting stuck in a local optimum, major

Table 1 Main materials data of a color TV set

Material	Mass (kg)	Mass percent (%)
Glass	1.53E+01	5.10E+01
Steel	3.60E+00	1.20E+01
Copper	2.40E+00	8.00E+00
Polystyrene(PS)	1.80E+00	6.00E+00
Polyvinyl chloride(PVC)	1.05E+00	3.50E+00
Aluminum	6.00E-01	2.00E+00
Polyethylene (PE)	3.00E-01	1.00E+00
Gold	4.26E-04	1.42E-03
Silver	1.22E-04	4.07E-04
Lead (Pb)	3.00E-02	1.00E-01
Chromium (Cr)	6.09E-05	2.03E-04
Mercury (Hg)	6.69E-09	2.23E-08
Nickel (Ni)	2.68E-03	8.93E-03
Zinc (Zn)	1.52E-03	5.07E-03
Antimony	1.03E-03	3.43E-03
Cobalt	9.13E-06	3.04E-05
Other materials	4.92E+00	1.64E+01
Total	3.00E+01	1.00E+02

processes and materials shall be included in the system as early as possible.

Firstly, depth-first search is adopted to identify the boundary of the system. Then priority level criterion for process- and flow-related interventions is used in the searching process. After obtaining all the processes of a system, the environmental impact of each unit process is evaluated and the processes are reordered according to the value of their environmental impacts multiplied with their masses. The top processes will be visited first.

4.3 Identification method

In order to execute the search algorithm, some initialization variables, such as initial system node and initial process node, need to be defined.

The initial system node is presented as: system={$\mathbf{P}$, L, color, FoP}, where $\mathbf{P}$ is the system intended to visit; L is the level of the system in the process tree; color is the visit status of system $\mathbf{P}$, (I) if it is not visited, then color=white, else (II) if ready to visit, then color=gray, else (III) if visited, then color=black; FoP is the type of the system $\mathbf{P}$, (I) if $\mathbf{P}$ is a primary system, then FoP=pri; else (II) if $\mathbf{P}$ is a flow-related subsystem, then FoP=sub-f; else (III) if $\mathbf{P}$ is a process-related subsystem, then FoP=sub-p. For example, the initial definition of the root node is, system$_1$={$\mathbf{P}_{\text{pri}}$, 0, white, pri}.

The initial process node is presented as: process={$\mathbf{p}$, $\mathbf{P}_{in}$, L, color}, where $\mathbf{p}$ is the process intended to visit; L is the level of the process in the process tree; color is the visit status of process $\mathbf{p}$, (I) if it is not visited, then color=white, else (II) if ready to visit, then color=gray, else (III) if visited, then color=black; and $\mathbf{P}_{in}$ is the system process $\mathbf{p}$ belonging to. For example the initialization definition of one process in the primary system is, process$_1$={$\mathbf{p}_1$, $\mathbf{P}_{\text{pri}}$, 0, white}.

The algorithm is as follows.

Step 1 Set the constraint criteria of economic processes, geographical, temporal and technical dimensions based on the purpose of the life cycle study. Define the set of process nodes RESULT=∅, and set the reference flow as the vector $\mathbf{f}$. Use the variable L to express system levels, and define SYSTEM={$\mathbf{P}_k$, L, white, FoP} (k=1, 2, …, n) as the set of systems considered, and PROCESS$_k$={$\mathbf{p}_{kj}$, $\mathbf{P}_k$, L, white} (j=1, 2, …, m) as the set of processes for system $\mathbf{P}_k$.

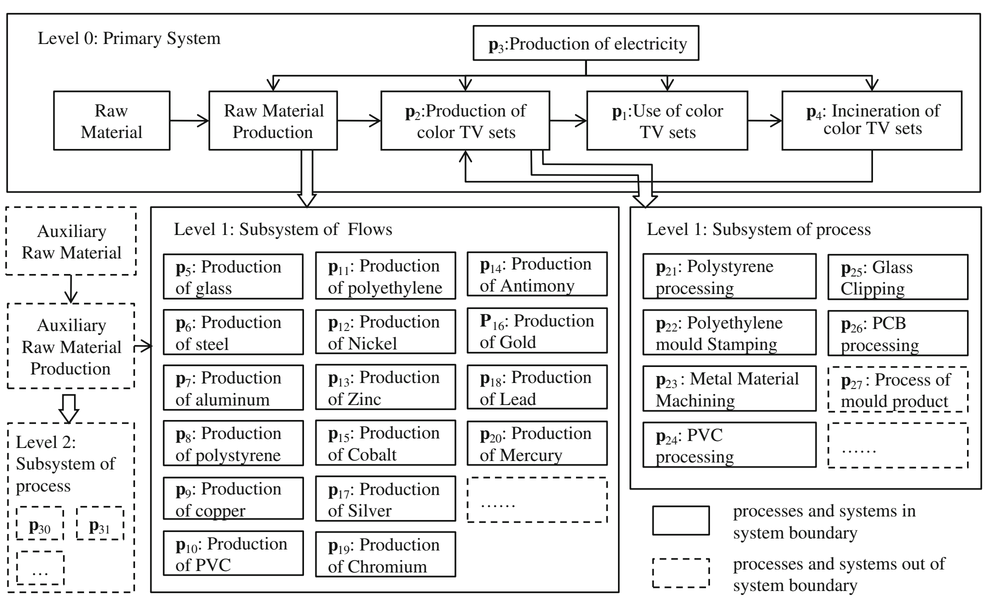


Fig. 7 Process tree of a color TV set life cycle

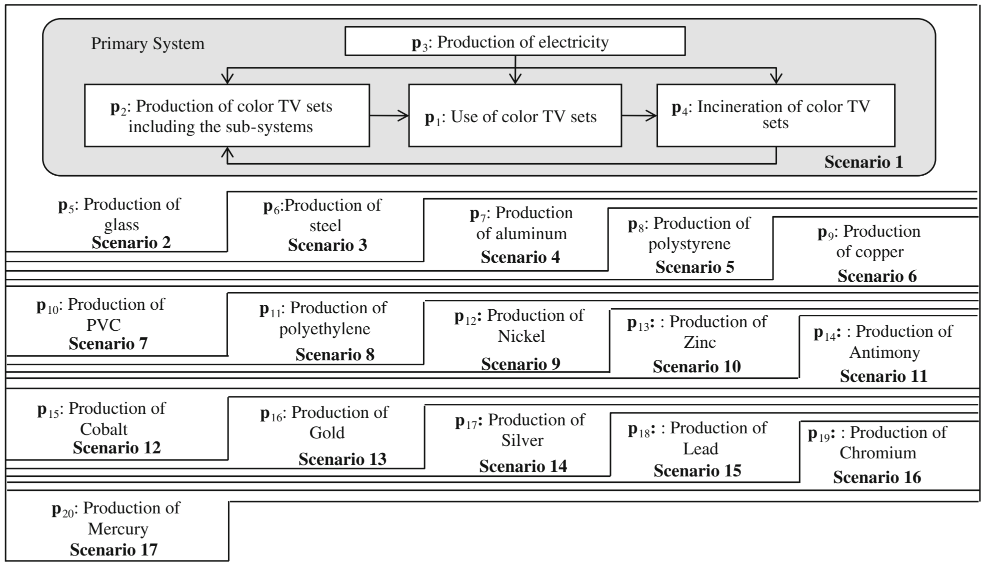


Fig. 8 The system boundaries of the different scenarios

Table 2 The inventories of the different system boundaries

Environmental emissions	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
CO_2	1.008539E+03	1.064040E+03	1.109011E+03	1.134451E+03	1.174890E+03	1.191701E+03
CO	0.000E+00	4.000E-03	4.000E-01	4.010E-01	4.010E-01	4.050E-01
CH_4	0.000E+00	0.000E+00	6.500E-02	7.900E-02	7.900E-02	7.900E-02
NO_2	5.082E+00	5.389E+00	5.524E+00	5.606E+00	5.810E+00	5.887E+00
SO_2	8.066E+00	8.587E+00	8.894E+00	9.104E+00	9.442E+00	9.560E+00
HCL	0.000E+00	0.000E+00	3.000E-03	3.000E-03	3.000E-03	6.000E-03
COD	0.000E+00	7.600E-03	9.000E-03	9.000E-03	9.000E-03	9.000E-03
BOD	0.000E+00	0.000E+00	1.800E-05	1.800E-05	1.800E-05	1.800E-05
Hard coal	-4.02978E+02	-4.33939E+02	-4.42582E+02	-4.55639E+02	-4.80461E+02	-4.99714E+02
Environmental emissions	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
CO_2	1.207680E+03	1.212315E+03	1.373866E+03	1.373883E+03	1.373901E+03	1.373916E+03
CO	4.050E-01	4.050E-01	4.640E-01	4.640E-01	4.640E-01	4.640E-01
CH_4	7.900E-02	8.300E-02	3.230E-01	3.230E-01	3.230E-01	3.230E-01
NO_2	5.952E+00	5.966E+00	6.671E+00	6.671E+00	6.671E+00	6.671E+00
SO_2	9.713E+00	9.747E+00	1.316E+01	1.316E+01	1.316E+01	1.316E+01
HCL	6.000E-03	6.000 E-03	2.000E-02	2.000E-02	2.000E-02	2.000E-02
COD	9.000E-03	9.000 E-03	1.750E-01	1.750E-01	1.750E-01	1.750E-01
BOD	1.800E-05	1.800E-05	1.610E-01	1.620E-01	1.620E-01	1.620E-01
Hard coal	-5.05739E+02	-5.07910E+02	-5.47482E+02	-5.47487E+02	-5.47492E+02	-5.47496E+02
Environmental emissions	Scenario 13	Scenario 14	Scenario 15	Scenario 16	Scenario 17	
CO_2	1.395696E+03	1.395699E+03	1.395798E+03	1.395803E+03	1.395803E+03	
CO	4.810E-01	4.810E-01	4.810E-01	4.810E-01	4.810E-01	
CH_4	3.590E-01	3.590E-01	3.590E-01	3.590E-01	3.590E-01	
NO_2	6.764E+00	6.764E+00	6.765E+00	6.765E+00	6.765E+00	
SO_2	1.327E+01	1.327E+01	1.328E+01	1.328E+01	1.328E+01	
HCL	2.200E-02	2.200E-02	2.200E-02	2.200E-02	2.200E-02	
COD	1.830E-01	1.830E-01	1.830E-01	1.830E-01	1.830E-01	
BOD	1.660E-01	1.660 E-01	1.660E-01	1.660E-01	1.660E-01	
Hard coal	-5.53787E+02	-5.53787E+02	-5.53813E+02	-5.53815E+02	-5.53815E+02	

Table 3 Environmental impacts of the processes considered

Environmental impacts	Scenario 1	Scenario2	Scenario 3	Scenario 4	Scenario5	Scenario 6
GWP	2.6349E+03	2.7886E+03	2.8791E+03	2.9311E+03	3.0368E+03	3.07817E+03
AP	1.2181E+01	1.2945E+01	1.3396E+01	1.3672E+01	1.4174E+01	1.4355E+01
EP	6.8610E+00	7.2753E+00	7.4583E+00	7.5687E+00	7.8441E+00	7.9482E+00
POCP	0.0000E+00	1.0000 E-04	1.2000 E-02	1.2000E-02	1.2000E-02	1.2200E-02
Environmental impacts	Scenario7	Scenario 8	Scenario 9	Scenario 10	Scenario11	Scenario 12
GWP	3.1152E+03	3.1243E+03	3.5176E+03	3.5177E+03	3.5177E+03	3.5178E+03
AP	1.4554E+01	1.4601E+01	1.8475E+01	1.8475E+01	1.8475E+01	1.8475E+01
EP	8.0369E+00	8.0553E+00	9.0105E+00	9.0106E+00	9.0107E+00	9.0108E+00
POCP	1.2200E-02	1.2200E-02	1.3900E-02	1.3900E-02	1.3900E-02	1.3900E-02
Environmental impacts	Scenario 13	Scenario 14	Scenario 15	Scenario 16	Scenario 17	Normalization (Wenzel et al. 1997)
GWP	3.5702E+03	3.5702E+03	3.5704E+03	3.5704E+03	3.5704E+03	8.700E+03 kg CO2-eq
AP	1.8696E+01	1.8696E+01	1.8698E+01	1.8698E+01	1.8698E+01	3.600E+01 kg SO2-eq
EP	9.1369E+00	9.1369E+00	9.1374E+00	9.1374E+00	9.1374E+00	6.200E+01 kg NO2-eq
POCP	1.4400E-02	1.4400E-02	1.4400E-02	1.4400E-02	1.4400E-02	6.500E-01 kg C2H4-eq

Step 2 Set $L=0$, for the primary system, $k=1$, $\mathbf{P}_k=\mathbf{P}_{\mathrm{pri}}$, set system$_k=\{\mathbf{P}_k, L, \text{black, pri}\}\in$SYSTEM.

Step 3 Find all process $\mathbf{p}_{kj}$ ($j=1, 2, \ldots, m$) of $\mathbf{P}_k$ based on the constraint criteria, and reorder $\mathbf{p}'_{kj}$ ($j=1, 2, \ldots, m$) according to theirs environmental impact. Set PROCESS$_k=\{\mathbf{p}'_{kj}, \mathbf{P}_k, L, \text{gray}\}(j=1, 2, \ldots, m)$. Get the flows of $\mathbf{p}'_{kj}$ ($j=1, 2, \ldots, m$). According to Definition 4, Set $\mathbf{P}_c=[\mathbf{p}'_{k1}, \mathbf{p}'_{k2},\ldots, \mathbf{p}'_{km}]$, $i=1$, $S_i=\{\mathbf{p}'_{k1}, \mathbf{p}'_{k2},\ldots, \mathbf{p}'_{km}\}$, then calculate the inventory vector $\mathbf{g}=\mathbf{B}\mathbf{A}^{-1}\mathbf{f}$. Assess the environmental impact of $\mathbf{P}_c$ and mark it as EI(S_i). Put process$_{kj}$ ($j=1, 2, \ldots, m$) in RESULT.

Step 4 Set $j=1$, get process$_{kj}=\{\mathbf{p}'_{kj}, \mathbf{P}_k, L, \text{black}\}\in$ PROCESS$_k$.

Step 5 Set $L=L+1$, $k=k+1$, Find subsystem $\mathbf{P}_k$ of $\mathbf{p}'_{kj}$ (or $\mathbf{p}'_{ku}$) (Each process only has one subsystem, see Section 2.2) by checking set R, set system$_k=\{\mathbf{P}_k, L, \text{black, FoP}\}$.

Step 6 Find all process $\mathbf{p}_{ku}$ ($u=1, 2, \ldots, v$) of $\mathbf{P}_k$ based on the constraint criteria, and reorder $\mathbf{p}'_{ku}$ ($u=1, 2, \ldots, v$) according to theirs environmental impact. Set PROCESS$_k=\{\mathbf{p}'_{ku}, \mathbf{P}_k, L, \text{gray}\}(u=1, 2, \ldots, v)$. Set $u=1$.

Step 7 Get process$_{ku}=\{\mathbf{p}'_{ku}, \mathbf{P}_k, L, \text{black}\}\in$PROCESS$_k$. Get the flows of $\mathbf{p}'_{ku}$. Set $\mathbf{P}'_{\mathrm{c}}=[\mathbf{P}_{\mathrm{c}}, \mathbf{p}'_{ku}]$, $S_{i+1}=S_i\cup\{\mathbf{p}'_{ku}\}$, then calculate the inventory vector $\mathbf{g}'=\mathbf{B}'\mathbf{A}'^{-1}\mathbf{f}$. Assess the environmental impact of $\mathbf{P}'_{\mathrm{c}}$ and mark it as EI(S_{i+1}). Put process$_{ku}$ in RESULT. Check

Table 4 Environmental impacts of the processes considered after normalization

Environmental impacts	Scenario 1	Scenario2	Scenario 3	Scenario 4	Scenario5	Scenario 6
GWP	3.029E-01	3.205E-01	3.309E-01	3.369E-01	3.491E-01	3.538E-01
AP	3.384E-01	3.596E-01	3.721E-01	3.798E-01	3.937E-01	3.987E-01
EP	1.125E-01	1.193E-01	1.223E-01	1.241E-01	1.286E-01	1.303E-01
POCP	0.000E+00	2.000E-04	1.850E-02	1.850E-02	1.850E-02	1.870E-02
Environmental impacts	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario11	Scenario 12
GWP	3.581E-01	3.591E-01	4.043E-01	4.043E-01	4.043E-01	4.043E-01
AP	4.043E-01	4.056E-01	5.132E-01	5.132E-01	5.132E-01	5.132E-01
EP	1.318E-01	1.321E-01	1.477E-01	1.477E-01	1.477E-01	1.477E-01
POCP	1.870E-02	1.870E-02	2.140E-02	2.140E-02	2.140E-02	2.140E-02
Environmental impacts	Scenario 13	Scenario 14	Scenario 15	Scenario16	Scenario 17	Weighting factor (Yang and Nielsen 2001)
GWP	4.104E-01	4.104E-01	4.104E-01	4.104E-01	4.104E-01	8.30E-01
AP	5.193E-01	5.193E-01	5.194E-01	5.194E-01	5.194E-01	7.30E-01
EP	1.498E-01	1.498E-01	1.498E-01	1.498E-01	1.498E-01	7.30E-01
POCP	2.220E-02	2.220E-02	2.220E-02	2.220E-02	2.220E-02	5.10E-01

Table 5 The overall environmental impact of a color TV set in its life cycle

Scenarios	Scenario 1	Scenario2	Scenario 3	Scenario 4	Scenario5	Scenario 6
Mass of flows considered in system boundary (kg)	1.424666E+03	1.527267E+03	1.585388E+03	1.625242E+03	1.691643E+03	1.730310E+03
Overall environmental impacts	5.8047580E-01	6.1569833E-01	6.4499979E-01	6.5689196E-01	6.8044296E-01	6.8939747E-01
Scenarios	Scenario7	Scenario 8	Scenario 9	Scenario10	Scenario 11	Scenario 12
Mass of flows considered in system boundary (kg)	1.754332E+03	1.761490E+03	1.967365E+03	1.967386E+03	1.967408E+03	1.967428E+03
Overall environmental impacts	6.9803967E-01	7.0007724E-01	8.2896557E-01	8.2897360E-01	8.2898517E-01	8.2899262E-01
Scenarios	Scenario13	Scenario 14	Scenario15	Scenario 16	Scenario 17	
Mass of flows considered in system boundary (kg)	1.995775E+03	1.995778E+03	1.995876E+03	1.995882265E+03	1.995882266E+03	
Overall environmental impacts	8.4039133E-01	8.4039226E-01	8.4045587E-01	8.404582619E-01	8.404582622E-01	

whether non-equality $\mathrm{EI}(S_{i+1})$ -$\mathrm{EI}(S_i)\leq\Delta\delta$ or $(\mathrm{EI}(S_{i+1})$-$\mathrm{EI}(S_i))/\Delta m\leq k_\delta$ is satisfied. If satisfied, then quit the search and return RESULT, else go to **Step 8**.

Step 8 Check whether there is subsystem of process $\mathbf{p}'_{ku}$ by checking set R, if true, then set $\mathbf{P}_c=\mathbf{P}'_c$ and $i=i+1$, go to **Step 5**; else check whether $u<v$, if true, then set $u=u+1$(the brother nodes), $\mathbf{P}_c=\mathbf{P}'_c$ and $i=i+1$, go to **Step 7**; else go to **Step 9**.

Step 9 Check whether $j<m$, if false, then quit the search and return RESULT; else set $j=j+1$, $L=L$-1, get $\mathrm{process}_{kj}=\{\mathrm{p}'_{kj},\ \mathrm{P}_k,\ L,\ \mathrm{black}\}\in\mathrm{PROCESS}_k$, set $\mathbf{P}_c=\mathbf{P}'_c$ and $i=i+1$, go to **Step 5**.

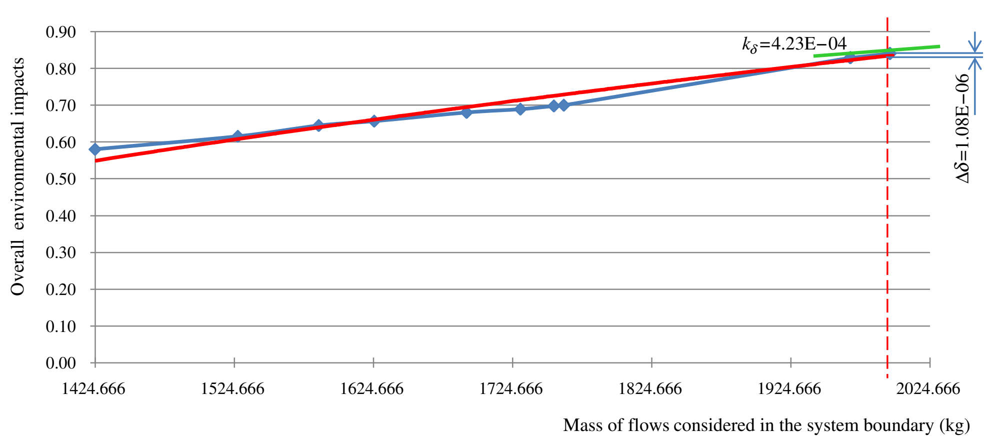
The search algorithm is shown in Fig. 5. After the algorithm is executed, the system boundary is described by the set RESULT. All the processes and systems being selected or omitted can be reported. Taking Fig. 2 as an example, the detailed steps of the boundary identification procedures are shown in Fig. 6.

5 Case study

In order to demonstrate the presented method in this study, a color TV set (screen: 25 inches; weight: 30 kg, Dodbiba et al. (2008) and Feng and Ma (2009)) is selected to analyze its life cycle environmental impact. Dodbiba and Feng considered only seven species of raw materials, which are glass, steel, copper, aluminum, PE, PVC and PS, while the data about printed circuit board (PCB) are neglected. In order to get a more complete analysis, the data of a desktop (Shrivastava et al. (2005) and Kulkarni et al. (2005)) are selected to discount the related data of the TV set. The motherboard of the desktop is selected to discount precious materials, hazardous materials and non-Ferrous materials in the PCB of the TV set. Precious materials include Gold and Silver; hazardous materials include Lead, Chromium, and Mercury; and non-Ferrous materials include Nickel, Zinc, Antimony and Cobalt. All the materials considered and their weights are listed in Table 1. According to Malmodin et al. (2001), the energy consumption related to PCB weight is 40 kWh/kg, since the weight of the TV set is 0.9 kg, so the energy consumption of PCB of TV set is 130 MJ, which is added to the total energy of the TV set manufacturing.

The functional unit for this study is 30 kg of the color TV set, with 10 years expected lifetime. The color TV set works 8 h every day, 300 days every year with 0.12 kW rated power, which means it works 24,000 h in 10 years. It is assumed that the recovery ratio for the discarded TV sets is 50 %. The discarded TV sets are manually disassembled, and their parts are separated for recycling and incinerating.

Fig. 9 The system boundary cure and the threshold of required precision



Therefore, economic processes dimension of the primary system is: Scope criterion={cradle to grave}. The economic processes dimension of the subsystem is: Scope criterion={cradle to gate}.

The constraint criterion of geographical dimension is: Geographical criterion={China}.

The constraint criterion of temporal dimension is: Temporal criterion=[year 1996, year 2005].

The constraint criterion of impact categories is: Impact categories criterion={Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP)}.

Figure 7 shows the process tree of a color TV set life cycle. There are four processes in the primary system of the TV set life cycle, which are marked as $\mathbf{p}_1$, $\mathbf{p}_2$, $\mathbf{p}_3$ and $\mathbf{p}_4$ after having sorted according to their environmental impacts. There are sixteen processes in the subsystem of raw materials production, which are marked as $\mathbf{p}_5$, $\mathbf{p}_6$, … and $\mathbf{p}_{20}$. There are six processes in the subsystem of the TV set production, which are marked as $\mathbf{p}_{21}$, $\mathbf{p}_{22}$, … and $\mathbf{p}_{26}$. In order to simplify the LCA process, the inventory of processes $\mathbf{p}_{21}$, $\mathbf{p}_{22}$, … and $\mathbf{p}_{26}$ are included in process $\mathbf{p}_2$.

According to the characteristic of the elementary flows of the process in the primary system and subsystems, the basis of the economic vector $\mathbf{a}_i$ and environmental vector $\mathbf{b}_i$ are defined (see Electronic Supplementary Material).

The reference vector is $(0, 0, 0, 24000, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)^{T}$. It is assumed that the recycling ratio of metal material is 50 %, the plastic wastes are incinerated for electricity production (Marvuglia et al. 2010). Then we get the technical matrix **A** and intervention matrix **B** referring to the process data of (Feng and Ma 2009) (see Electronic Supplementary Material)

Matrix A is square and non-singular, hence it is invertible. Based on the research, the first four processes are considered as scenario one, the first five processes as scenario two and so on. Figure 8 shows the system boundaries of the different scenarios of the color TV set life cycle. According to definition 4, inventory can be calculated based on the processes considered in the TV set life cycle. The multiplication of the inverse of the technology matrix of each scenario with the final demand vector yields the scaling vector **s**. Then multiplication of the intervention matrix with the scaling vector **s** yields the inventory vectors of the environmental emissions and recourse consumptions. Table 2 shows the inventory vectors in a tabular form.

Multiplication of the characterization factor (Yang et al. 2002) with the quantities of environmental emissions yields the environmental impacts of the TV set. After adding the weighting factor of each environmental impact (Yang and Nielsen 2001), we get the overall environmental impact indicators of different scenarios (as shown in Tables 3, 4 and 5).

Based on Table 5, we plot the system boundary fitting curve which refers to the relationship between the mass of the input flows of the processes considered and their corresponding environmental impact indicators (as shown in Fig. 9). According to the threshold rules mentioned in Section 4.1, the threshold is set at k_δ<=4.25E-04 for this case. After performing the calculation, it was observed that the point of scenario 13 satisfied the threshold where the value of k_δ and $\Delta\delta$ approach zero, k_δ= 4.23E-04 and $\Delta\delta$=1.08E-06.

The result shows the overall environmental impact exhibits a slow growth after a certain number of processes considered; the gradient of the fitting curve trends to zero gradually, which demonstrates that the methodology presented is a concise and effective method to identify the boundary of LCA.

6 Concluding remarks

In the process of Scope Definition and Inventory Analysis in LCA, ideally, all the inputs and outputs related to the entire life cycle of a product should be considered, and the accumulated results are estimated based on the data collected from each flow. However, in many cases there will be insufficient time, data, or resources to conduct such a comprehensive study. Therefore, the scientific issue of boundary identification has been a significant challenge to LCA researchers. To solve this problem, a hierarchical relationship of product system is analyzed in detail and the definitions of unit process, system and process tree is put forward to define the entire product system. Then the system boundary curve model of the LCA and two threshold rules are presented to judge whether the system boundary satisfies the research requirement. Quantitative criteria from environmental, geographical, temporal and technical dimensions are presented to limit boundaries of LCA. A depth-first search based algorithm to obtain a scientific boundary is established by evaluating the environmental contribution of each process in a studied system. A case study is conducted on a color TV set to demonstrate the method of boundary identification. The results shows that environmental impact indicator exhibits a slow growth after a certain number of processes are considered and the gradient of the fitting curve trends to zero gradually, which validates the system boundary curve presented in the boundary model. The method presented in this paper can be used to identify system boundaries of an LCA study.

The international LCA standard ISO 14044 states that the steps of normalization, grouping and weighting in LCIA are optional depending on the goal and scope of the study. This paper presents a theoretically complete framework and the steps of LCIA are discussed in the system boundary curve model. However, these three steps are not a rigid requirement to apply the approach. For example, the impact indicators obtained from the step of characterization also satisfies the

system boundary curve model developed in the paper. Since the overall environmental impact indicator integrates individual environmental impacts into a comprehensive indicator, if the steps of grouping and weighting are included in the study, substituting the overall environmental impact indicator $\mathrm{EI}(S_i)$ into the threshold rules is a convenient way to evaluate the system boundary. The approach developed in this paper is suitable for a product or a process system. As for comparative LCA in which similar processes might be excluded from the analysis, more research is needed to see whether the system boundary curve model is suitable. This topic can be an extension of our current research in the future. As for the approach itself, sensitivity and uncertainty analysis, the method of how to quickly reach the value of δ, and how to determine accuracy requirement of $\Delta\delta$ and k_δ will be studied in the future.

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